

**Microlensing events of the LMC are better explained
by stars within the LMC than by MACHOs**

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ABSTRACT

The recently reported microlensing events of the LMC have caused much excitement, and have been interpreted as due to ‘dark objects’ (MACHOs) in the halo of our Galaxy. It is shown here that the stars within the LMC play a dominant role as gravitational lenses and can indeed account for the observed events.

For observations within the bar of the LMC, the probability of microlensing being caused by a star within the LMC is found to be $\sim 5 \times 10^{-8}$. Outside of the bar, the probability of microlensing being caused by a star in the LMC is 4 to 12 times lower. The MACHO event (Alcock et al. 1993) and one of the EROS events (Aubourg et al. 1993) lie within the bar for which the probability of microlensing is consistent with being caused by an object within the LMC.

If the stars within the LMC play a dominant role as lenses, the events should be concentrated towards the center of the LMC. On the other hand, if MACHOs play a dominant role as lenses then, for a given number of monitored stars, the events should be uniformly distributed over the whole area of the LMC. Thus the galactic and the LMC lenses can be statistically distinguished in most cases.

It is further shown that, under certain conditions, the light curve of an event caused by a star within the LMC would be different from the one caused by a MACHO. This can also be a distinguishing signature, and seems to have been observed in case of the MACHO event. The fit discrepancy near the peak which the authors say “is not yet understood” would be a natural consequence if the event is caused by an object within the LMC, which further indicates that the lensing is due to a low mass star within the LMC itself.

1. Introduction

Most galaxies are known to have flat rotation curves (Begeman, 1987; Sanders and Begeman 1994). In the outer parts of the galaxies in particular, the visible matter falls far short of what is required to explain the flat rotation curves. In our own Galaxy, the rotation curve is observed to be flat up to at least 16 kpc from the center (Fich et al. 1989). The scenarios proposed to explain the flat rotation curves are either departure from Newtonian dynamics in large scale, or presence of dark matter (for a review see Sanders 1990 and Broeils 1991). In the latter and more conventional scenario, the rotation curves would imply that a significant part of the mass of the galaxies, including our own, resides in the halo in some form of dark matter. The nature of this dark matter has been hypothesized to be in either of the two forms: MACHOs (i.e. massive compact halo objects which is a collective term for ‘Jupiters’, brown dwarfs, red dwarfs, white dwarfs, neutron stars or black holes); or elementary particles such as massive neutrinos, axions or WIMPs (weakly interacting massive particles such as photinos etc.). One important distinguishing factor of the MACHOs is that they can have detectable gravitational effects and can cause “gravitational microlensing” of background stars.

Einstein (1936) was the first to point out that a star can act as a gravitational lens for another background star, if the two are sufficiently close to each other in the line of sight. Given the observational capabilities of that time, Einstein had however considered this to be a purely theoretical exercise and had remarked that there was “no hope of observing such a phenomenon directly”.

The observational capabilities have improved remarkably since then. More recently, Paczyński (1986) worked out the probability of such microlensing events by MACHOs and showed that if the halo of our Galaxy is made up of MACHOs, the probability of finding them through microlensing is 5×10^{-7} , independent of their mass distribution. He suggested an experiment to look for such events using the LMC stars. Further details of this idea were worked out by Griest (1991). Such an experiment was taken up by 2 groups who have reported their first results (Alcock et al. 1993; Aubourg et al. 1993).

2. The experimental results

The results from the MACHO experiment (Alcock et al. 1993) are from the monitoring of 1.8 million stars in the bar of the LMC, both in blue and red wavelengths, for a period of one year, which led to the detection of one event. More recently, it has been reported that the analysis of all the data, which involves monitoring of 8.3 million stars in the region of the bar over 2 years, has led to the detection of 4 events (Cook et al. 1994). The EROS experiment (Aubourg et al. 1993) involves 2 programs: one involves monitoring of 8 million stars over a field of 5×5 degrees using Schmidt plates in red and blue, with a

sampling rate of one or two per night over a period of 3 years. The second program involves monitoring of 100,000 stars in red and blue wavelengths, over an area of 1×0.4 square degrees with a sampling rate of about half an hour, for about 7 months. The analysis of 40% of data of the first program led to the detection of 2 events, and no event was detected in the second program. The details of the published events are listed in Table 1.

3. Concerns if the microlensing is caused by MACHOs

If these are genuine microlensing events by galactic halo objects, this could potentially herald an end to the problem of dark matter. But this has also been the cause for some concern: if these events are caused by the objects in the halo, it would lead to some problems in terms of stellar evolution and the theory of galaxy formation (Hogan, 1993).

Recent work on deuterium abundance derived from the observations of a quasar suggests that the dark halos of galaxies may well be nonbaryonic (Songaila et al. 1994).

In case of the MACHO event, which has the highest signal to noise ratio, there is a discrepancy between the best fit and the observed light curve near the peak of the light curve. This consistently repeats both in the blue and in the red, and according to the authors this “fit discrepancy near the peak is not yet understood”. Furthermore, the rate of microlensing events as observed seems to be lower than expected from the dark halo, and it is important to estimate the rate expected from the stars that are known to exist in our galaxy and in the LMC. The analyses for the galactic stars and the LMC halo have been done, but the importance of the LMC stars had been overlooked so far. Sahu (1994) has recently shown that the stars within the LMC indeed play a dominant role as gravitational lenses, the full details of the probability analysis is presented here. It should be noted here that, for the microlensing events of the galactic bulge stars (Udalski et al. 1993; Udalski et al. 1994), the stars within the bulge also play an important role as gravitational lenses, the analysis of which has recently been done by Kiraga and Paczyński (1994). Furthermore, this paper presents the analysis of the light curve and shows that if a star within the LMC acts as a lens, the source can be extended which reproduces the light curve better. Before attempting to analyse the light curve in detail, let us first see in detail the probability of this scenario.

4. Analysis of the probability

4.1 Mass of the bar and stellar density

To calculate the probability of the microlensing being caused by a star in the LMC itself, we need to know the stellar mass density in the LMC. Let us first confine ourselves to the bar of the LMC. From the surface luminosity, it is estimated that the observed luminosity of the bar is about 10 to 12 % of the total observed luminosity of the LMC in the optical

wavelengths (De Vaucouleurs and Freeman 1973, Bothum and Thompson 1988). To see whether the effect of extinction is important and to account for it, we note that the extinction in the region of the bar, as derived from the 100 μm IRAS maps is between 12 and 24 MJy per steradian with an average value of about 17 MJy per steradian (Schwering and Israel 1990), which translates to an average extinction of about 1.5 mag in the V band (Laureijs, 1989). This value is consistent with the value deduced by Hodge (1991) from background galaxy counts and is also consistent with the value derived from the observations of the most reddened stars in the region (Isserstedt 1975). The average extinction in the outer regions is about 0.3 to 0.4 magnitudes. It is perhaps worth noting here that, as we will see later, errors in extinction measurements have only very little effect on the final probability. To see how the extinction affects the mass, let us assume that the extinction is uniform in depth, and let d be the total depth. Thus for any line of sight, if A_v is the total extinction, the ratio of the observed to the true luminosity at that point

$$\frac{L_{obs}}{L_{true}} = \frac{1}{d} \int_0^d 2.5^{-A_v z/d} dz = \frac{1 - e^{-0.916 A_v}}{0.916 A_v} \quad (1)$$

where z is the direction of the line of sight.

Using $A_v=1.5$ mag for the bar, and 0.3 to 0.44 mag for the region outside, we get

$$\left[\frac{L_{obs}}{L_{true}} \right]_{bar} = 0.54 \text{ and } \left[\frac{L_{obs}}{L_{true}} \right]_{out} = 0.82 \text{ to } 0.87$$

Now, using the fact that $(L_{obs})_{bar}/(L_{obs})_{tot} = 0.1$ to 0.12 , and after a little algebra we get,

$$\frac{(L_{true})_{bar}}{(L_{true})_{Tot}} = 0.14 \text{ to } 0.18$$

Thus the true luminosity of the bar is about 14 to 18 % of the total luminosity of the LMC. The total mass of the LMC, as determined from various methods, ranges from 6×10^9 to $15 \times 10^9 M_\odot$ (De Vaucouleurs and Freeman, 1973). (In case of the LMC, there is no significant discrepancy between the mass derived from the observed luminosity and the mass derived from the velocity dispersion.) Assuming that the mass to light ratio in the bar and the outer parts are the same, we get the mass of the bar to be in the range $1 \times 10^9 M_\odot$ to $2.7 \times 10^9 M_\odot$. In our subsequent calculations, we will round off the mean and use $2 \times 10^9 M_\odot$ as the mass of the bar. Considering the fact that the LMC is gas poor and only about 5% of the LMC mass is neutral hydrogen (Westerlund 1990, Israel and de Graauw 1991, Rohlfs et al. 1984), we will neglect the contribution of gas to the mass and assume this entire mass to be made up of stars.

4.2 Expected probability of microlensing in the region of the bar

To calculate the probability of microlensing, let us assume that there are N_{tot} stars being monitored. We note that, the stars that are farther away, have more stars in front of them, thus having a larger probability of being microlensed. But the observed number density of stars becomes less at larger depths because of extinction. Thus, in order to correctly calculate the probability, we must know how the extinction affects the observed number of stars with depth. To make life easier, we can take the current monitoring programs and the magnitude limits to calculate the probability. We note that the limiting magnitude of the current surveys are about 20 to 21, which at the distance of LMC, corresponds to an absolute magnitude of 1.5 to 2.5. So the magnitude of the stars that can be observed at the near side is 1.5 to 2.5 whereas the magnitude of the stars at the far end is 1.5 magnitude brighter. If the distribution of stars among different spectral types is assumed to be similar to what is observed in the solar neighborhood, then the difference in stellar number density from front end to the back is about 3 (Allen 1973). Similar results are found from HST observations of LMC clusters (Gilmozzi et al. 1994). (If the extinction is 3 magnitudes, then this value is about 10. As it turns out, the effect of extinction is small. If the extinction is larger, the mass of the bar becomes larger thus increasing the probability of microlensing. But the extinction effectively reduces the observed number of stars which are at a larger depth which have the larger probability of being microlensed, thus decreasing the probability. These 2 effects compensate for each other the net effect is that the probability decreases with extinction, but only slightly. If the extinction is 3 magnitudes instead of 1.5, the net probability changes only by less than 50%. Furthermore, at the magnitudes considered here, the age is not expected to play a significant role, so to a good approximation, the spectral distribution of the stars can be assumed to be similar to that in the solar neighborhood for the probability calculation.)

Assuming the extinction to be uniform in depth, we can express the observed number of stars at any layer dz , at a depth of z , as

$$N_{obs}(z) = N_z 3^{-\frac{z}{d}} dz \quad (2)$$

where N_z is the observed number of stars per unit depth in absence of extinction i.e, the observed number of stars per unit depth at the near side. If N_{tot} is the total number of stars being monitored, then

$$N_{tot} = \int_0^d N_z 3^{-\frac{z}{d}} dz = N_z d \left[\frac{1 - 1/\ln 3}{\ln 3} \right] = 0.6 N_z d \quad (3)$$

Substituting eq. 3 in eq. 2, we get

$$N_{obs}(z) \simeq \frac{N_{tot}}{0.6d} 3^{-\frac{z}{d}} dz \quad (4)$$

The fraction of area covered by the Einstein rings of all the individual stars lying in the front of this layer can be expressed as

$$A_f(z) = \int_0^z \pi R_E^2(z) n(z) dz \quad (5)$$

where $n(z)$ is the stellar number density at depth z . Since $n = \rho/m$ and $R_E^2 \propto m$ where ρ is the stellar mass density and m is the mass of the star

$$A_f(z) = \frac{4\pi G}{c^2} \int_0^z \rho(z) z dz \quad (6)$$

which is thus independent of the mass distribution. Assuming the stellar density to be uniform with depth

$$A_f(z) = \frac{2\pi G \rho z^2}{c^2} \quad (7)$$

From Eq. 4 and 7, the instantaneous probability of observing one microlensing event, when N_{tot} stars are being observed, is

$$P = \int_0^d N_{obs}(z) A_f(z) dz = \frac{2N_{tot}\pi G \rho}{0.6dc^2} \int_0^d 3^{-\frac{z}{d}} z^2 dz \quad (8)$$

Strictly speaking, this is valid for $P \ll 1$, which is the case here. The optical depth τ , which is equivalent to the probability of any star being microlensed at a given time is P/N_{tot} , is easily obtained by solving eq. 8 as

$$\tau \simeq \frac{0.5\pi G \rho d^2}{c^2} \quad (9)$$

For the value of ρ , we can substitute,

$$\rho = \frac{M}{LWd} \quad (10)$$

where L , W , d and M are the length, width, depth and mass of the bar respectively.

Assuming $L=3000\text{pc}$, $W=d=600\text{pc}$ and $M = 2 \times 10^9 M_\odot$, and substituting eq.10 in eq.9, we get,

$$\tau_{bar} \simeq 5 \times 10^{-8} \quad (11)$$

with some uncertainty due to the uncertainties in the size and mass of the bar. It must be mentioned here that the value of the optical depth calculated above is an average value for

the whole bar. Since the luminosity gradient in the bar itself is about 30% from the center to the outer parts (Bothum and Thompson 1988), the optical depth would be slightly higher in the central region of the bar, and slightly lower in the outer region.

It is clear from Eqs. 9 and 10 that $\tau \propto d$. In absence of any more accurate information, we have used the depth to be the same as the width and have neglected any inclination effect. In the literature one finds that the bar can be as thin as the disk itself (Binney and Tremaine 1987). So, considering the fact that the thickness of the LMC disk is about 300pc, and the inclination is about 45 degrees (Westerlund 1991), the depth can be about 450pc in the extreme case, thus the effect due to the uncertainty in d can be 25% at the most.

Carrying out an identical analysis for the region outside the bar it is easy to see that, if the depth of the LMC disk is between 100 to 300pc (Feast, 1989), the optical depth in the region outside the bar is about 4 to 12 times smaller.

4.3. Comparison with observed probabilities

The MACHO event lies in the central region of the bar. Keeping in mind the uncertainties involved in the estimation of optical depth on the basis of the single published MACHO event, we can only say that it seems to be well below the optical depth of 5×10^{-7} expected from a dark halo made up entirely of MACHOs, and is consistent with the optical depth calculated above. Extending an identical analysis for the more recent results of 4 events reported from the monitoring of 8.3 million stars over a period of 2 years, the estimated observed probability is found to be indeed very close to the value calculated above, although there is some uncertainty in the value of the detection efficiency. In case of the EROS events, one event lies in the outer region of the bar, the other is far from the bar, and the optical depth has been estimated to be higher ($\sim 2 \times 10^{-7}$, Gould et al. 1994). But Gould et al. (1994) also suggest that there may be some systematic effects and the detection efficiencies may be uncertain. The situation will be clearer as more events are observed, particularly events with higher magnifications (see below), and we must wait for more events to be observed before making any direct comparison with the calculated optical depth.

Given the fact that the number involved in the statistics is small, and the fact that the calculations are rather straight forward and do not involve any unknown quantities or quantities with large uncertainties, the observed and the expected probabilities are certainly not inconsistent with each other.

4.4. Optical depth to microlensing by objects other than the LMC stars

The probability of microlensing due to stars in the disk and halo of our own galaxy has been

discussed by Gould et al. (1994) and the possible contribution of LMC halo was discussed by Gould (1992). The probability of the events being caused by the expected number of white dwarfs in the halo also appears to be too small. Apart from other theoretical reasons, the mass of the objects derived from the observed events do not agree well with this being caused by the the white dwarfs in the halo since they have a mass distribution which is highly peaked around $0.6 M_{\odot}$ (Weideman 1990).

5. Can we observationally distinguish between a MACHO and a star in the LMC?

This probability analysis may be enough for most astronomers to abandon the idea of MACHOs since the microlensing can be effectively caused by the known stellar population in the LMC itself and one does not need to resort to unknown objects such as MACHOs for an explanation. However, let us go one step further and investigate whether there is a distinguishing feature which can tell us whether the microlensing is caused by a MACHO or a star in the LMC. We will now see that under certain conditions, the fit discrepancy near the peak of the light curve can indeed be a distinguishing feature of the microlensing being caused by an object within the LMC. Let us see this in detail.

The amplification sharply rises when the lensing object comes close to being perfectly aligned with the source. The physical reason for this is that when the lensing object and the source are perfectly aligned, the image becomes a ring (also called the Einstein ring) instead of two separate images and thus the amplification rises sharply. [For details, see Paczyński, 1986]. In the case of lensing by MACHOs, R_E is of the order of $1.2 \times 10^{14} \sqrt{\frac{M}{M_{\odot}}}$ cm, assuming $D_d = 10$ kpc and $D_s = 55$ kpc which, at the source plane, is $\sim 10^{15} \sqrt{\frac{M}{M_{\odot}}}$ cm. The diameter of the source is thus 2 to 3 orders of magnitude smaller even if the lensing object is $\sim 0.1 M_{\odot}$. Thus the probability of the source and the lens being perfectly aligned is extremely small, and can happen only for events with extremely small u ($\lesssim 0.01$), which is unlikely and certainly not the case in the observed events. However, the value of R_E projected to the source plane can be much smaller if the lensing object is close to the source. For example, if we consider a typical distance of about 100 pc between the source and the lens, $R_E \simeq 10^{13} \sqrt{\frac{M}{M_{\odot}}}$ cm, which, for a $0.1 M_{\odot}$ lens, is only about about 3 times smaller than the typical radius of a red giant. Thus, in order that at least a part of the source is perfectly aligned with the lensing object, the impact parameter has to be $\lesssim 0.3$, which may explain the fit discrepancy near the peak of the light curve.

Note also that for the maximum amplification to be appreciable, the source size must not be too large for a different reason. If it is too large, even if both objects are perfectly aligned, most of the source is still not perfectly aligned with the source, this reduces the

maximum amplification. This is given by (Paczynski 1986)

$$A_{max} = [1 + \frac{4R_E^2}{r_0^2}]^{\frac{1}{2}} \quad (12)$$

5.1 Light curve due to an extended source

Assuming the source to be extended, let us calculate the amplifications. A general methodology for such a case was developed by Bontz (1979). The geometry of our particular case however (shown in Fig. 1) enables us to develop a simpler solution, which is found to be more suitable for numerical integrations. A mathematical approximation and the resulting analytical solution for such a case has also been given by Schneider et al. (1992) which, unfortunately for our purpose, does not have sufficient accuracy just at the transition point where the fit discrepancy begins to occur. Nevertheless, this analytical expression was found to be very useful in providing a constant check on the correctness of the numerical algorithm used here to calculate the light curve.

In a general case, the amplification caused by an extended source would be given by (Eq. 6.81 of Schneider et al. 1992)

$$\frac{\int d^2y I(y) \mu_p(y)}{\int d^2y I(y)} \quad (13)$$

where $I(y)$ is the surface brightness profile of the source, $\mu_p(y)$ is the amplification of a point source at point y , and the integration is carried out over the entire surface of the source.

Let us assume the source to be a disk of uniform brightness with radius r_0 and let u be the impact parameter ($=l/R_E$). y_0 be the distance between the lens and the center of the source projected onto the lens plane. Let us choose a circular coordinate system and let (r, θ) be the representative point which is at a distance y from the lens. From Fig. 1 we see that

$$y = \sqrt{y_0^2 + r^2 - 2 y_0 r \cos(\gamma)} \quad (14)$$

where

$$y_0 = \sqrt{x_0^2 + l^2}, \quad \gamma = \pi - \theta - \alpha \text{ and } \alpha = \sin^{-1}(l/y_0) \quad (15)$$

i.e.

$$y = \sqrt{y_0^2 + r^2 + 2 y_0 r \cos(\alpha + \theta)} \quad (16)$$

The amplification can be written as

$$\mu_p(y) = \frac{y^2 + 2}{y(y^2 + 4)^{1/2}} \quad (17)$$

Thus from eq.(13) the amplification can be expressed as

$$\frac{\int_0^{r_0} \int_0^{2\pi} \frac{y^2+2}{y(y^2+4)^{1/2}} y \, dr \, d\theta}{\int_0^{r_0} \int_0^{2\pi} y \, dr \, d\theta} \quad (18)$$

This is an expression suitable for numerical integration and can be easily integrated. The light curve can be reproduced as a function of time t , which is related to x_0 through the relation $x_0 = (R_E/t_0)t$ where t_0 is the timescale of microlensing (which is the time taken by the lens to cross its own Einstein ring). y in turn, is related to x_0 through eq.15 and 16.

Since I myself do not have the original data, I digitised the published light curve, in order to facilitate my attempts on fitting the light curve. Hence the error bars are not shown here, although the error bars at the points near the peak were also carefully digitised. The light curve was numerically calculated for different values of u and r_0 to reproduce the observed curve. The best fit to the light curve is obtained for $u = 0.17$ and the value of r_0/R_E between 0.17 and 0.175, which is shown in Fig.2. The solid curve is the best fit obtained using the lens to be a MACHO, and the dotted curve is obtained assuming the lens to be a star within the LMC. As is clear, the curve due to a MACHO has a significant discrepancy at the peak of the light curve both in the blue and in the red which is reduced in case of the best-fit light curve with a star in the LMC as the lens.

For a χ^2 analysis, let us first consider the red light curve, the observations of which have a higher signal to noise ratio. The total χ^2 gain, defined as $\Sigma\{[A(obs) - A(MACHO)]/\sigma\}^2 - \{[A(obs) - A(LMCstar)]/\sigma\}^2$ where A refers to the amplification, is about 7.3 units if we consider the 4 points near the peak. For the blue light curve, which has a lower S/N, the total χ^2 gain for these 4 points is about 4 units. For other points, both curves are practically identical.

It must be emphasized here that the source is not always extended for an LMC lens. The source would be point like for smaller values of r_0/R_E (which would be the case if the mass of the lens is slightly higher, or, the distance between the source and the lens is slightly higher). As shown in the next section, the solution becomes fairly unique if the light curve can be reproduced by an extended source approximation.

6. Mass of the lenses and further confirmation of the scenario

If this extended source approximation is valid, we can use the value of u and r_0/R_E as calculated in the preceding section and proceed to calculate some physical parameters. The source, from its color and luminosity, has been inferred to be a clump giant, for which we can assume the radius to be $r_0 = 7 \times 10^{11}$ cm. Now,

$$\frac{r_0}{R_E} = \frac{r_0 \, c}{\sqrt{4GM D}} \simeq 0.17; D \simeq D_{ds} \quad (19)$$

i.e.

$$\sqrt{\frac{M}{M_{\odot}} \frac{D}{100pc}} \simeq 0.3 \quad (20)$$

The mass the lens can also be expressed as

$$M \simeq \frac{[tV_e c]^2}{16GD(1-u^2)} \quad (21)$$

From Eq. 20 and 21, which now provide a consistency check, we get

$$\sqrt{\frac{M}{M_{\odot}} \frac{D}{100pc}} = 0.44 \left(\frac{V_e}{40km s^{-1}} \right) \simeq 0.3 \quad (22)$$

Thus, irrespective of the value of M and D for this particular case, we get the value of V_e to be $\sim 27 \text{ km s}^{-1}$. The fact that this is similar to the value of dispersion obtained for the bar from radio observations (Rohlf et al. 1984) further confirms the validity of this scenario. The mass of the lens can thus be expressed as

$$M \simeq 0.1 \frac{100pc}{D} M_{\odot} \quad (22)$$

Although the signal to noise ratio in the EROS events might not allow us to do such a detailed analysis of the light curve, the observed amplifications would imply that the source can be approximated as a point source. For the point source approximation to be valid, we need $r_0/R_E < 1$ (Fig. 1) which provides a lower limit to the mass of the lens. An upper limit to the mass of the lens comes from equation 21 (using the velocity dispersion). The mass range thus derived is shown in Table 1.

7. Conclusions

No dark matter is required to explain the observed microlensing events of the LMC stars. The probability of microlensing being caused by a star in the bar of the LMC is found to be consistent with the observations. Detailed analysis of the light curve of the event with the best signal to noise shows that the light curve is better reproduced by a star in the LMC than by a MACHO, and indicates that a low mass star in the LMC must be the cause of the microlensing.

The LMC induced events should be strongly clustered towards the central region of the LMC. (They should be proportional to the number of monitored stars multiplied by the integrated stellar mass density along the line of sight.) In case of the galactic events, for a given number of monitored stars, the events should be uniformly distributed over the whole of LMC. (They should be simply proportional to the number of monitored

stars.) Furthermore, under certain conditions, the observed light curve in case of the LMC event can be different from the light curve due to a galactic lens. Thus the two scenarios can be distinguished statistically in most cases, and individually in a few cases. Such a distinguishing feature seems to have already been seen in case of the light curve of the MACHO event.

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References

- Allen, C.W., 1973, *Astrophysical Quantities*, 3rd Edition, The Athlone Press
- Alcock, C. et al. 1993, *Nature*, **365**, 621
- Aubourg et al. 1993, *Nature*, **365**, 623
- Begeman, K., 1987, Ph.D. thesis, Groningen University
- Binney J., Tremaine, S., 1987, *Galactic Dynamics*, Princeton University Press
- Bontz, R.J., 1979, *Astrophys. J.*, **233**, 402
- Bothum, G.D., Thompson, I.B., 1988, *Astron. J.*, **96**, 877
- Broeils, A., 1991, Ph.D. thesis, Groningen University
- Cook, K., et al., 1994, *Bull. Am. Astron. Soc.*, **26**, 912
- De Vaucouleurs, G, Freeman, K.C., 1973, *Vistas Astron.* **14**, 163
- Einstein, A., 1936, *Science*, **84**, 506
- Feast, M., 1989, “Recent Developments in Magellanic Cloud Research”, *Observatoire de Paris* (eds de Boer, K.S., Spite, F. & Stasinska, G.) 75
- Fich, M, Blitz, L, Stark, A., 1989, *ApJ*, **342**, 272
- Gilmozzi, R., Kinney, E.K., Ewald, S.P., Panagia, N., Romaniello, M., 1994, Preprint
- Gould, A. 1992, *ApJ*, 404, 451
- Gould, A., Miralda-Escudé, J., Bahcall, J.N., 1994, *ApJ Lett.*, **423**, L105
- Griest, K, 1991, *ApJ*, **366**, 412
- Hodge, P., 1991, *IAU Symp.* 148 “The Magellanic Clouds”, Ed. R. Haynes and D. Milne, Kluwer Academic Publishers, p57
- Hogan C.J., 1993, *Nature*, 365, 602
- Israel, F.P., de Graauw, Th., 1991, *IAU Symp.* 148 “The Magellanic Clouds”, Ed. R. Haynes and D. Milne, Kluwer Academic Publishers, p45
- Kiraga, M., and Paczyński, B. 1994, *ApJ* (in press)
- Kroupa, P, Tout, C.A., Gilmore, G., 1993, *MNRAS*, **262**, 545
- Isserstedt, J., 1975, *Astron. Astrophys.* **41**, 175

- Laureijs R., 1989, Ph.D. thesis, Groningen University, p85
- Paczynski, B., 1986, ApJ, **304**, 1
- Rohlfs, K., Kreitschmann, J., Siegman, B.C., Feitzinger, J.V., 1984, Astron. Astrophys. **137**, 343
- Sahu, K.C., 1994, Nature, **370**, 265
- Sanders, R.H., 1990, Astron. Astrophys. Rev., **2**, 1
- Sanders, R.H., and Begeman, K. 1994, MNRAS, 266, 360
- Schneider, P, Ehlers, J. and Falco, E.E., 1992, “Gravitational Lensing”, published by Springer-Verlag.
- Schwering P.B.W., Israel, F.P., 1990, “Atlas and Catalog of Infrared Sources in Magellanic Clouds”, Kluwer Academic Publishers.
- Songaila L.L., Cowie, C.J., Hogan, C.J., Rugers, M., 1994, Nature **368**, 599
- Udalski, A., et al. 1993, Acta Astr., 43, 289
- Udalski, A., et al. 1993, Acta Astr., 44, 165
- Weidemann, V., 1990, Ann. Rev. Astron Astrophys., **28**, 103
- Westerlund, B., 1990, Astron. Astrophys. Rev., **2**, 29
- Westerlund, B., 1991, IAU Symp. 148 “The Magellanic Clouds”, Ed. R. Haynes and D. Milne, Kluwer Academic Publishers, p15

Figure captions

Fig. 1 Schematic of the geometry of the microlensing used for calculation of the light curve. The lens is assumed to be a point lens. Note that the Einstein ring radius associated with an LMC lens is much smaller than either a disk or a halo lens. Consequently, the minimum impact parameter u ($= l/R_E$) needed for a part of the source to be perfectly aligned with the lens can be higher. This implies that the source can be resolved at much smaller magnifications if the lens resides in the LMC. See text for the details of the symbols used.

Fig. 2. The observed microlensing events both in blue and red. The best fit due to a MACHO is shown by a solid curve. The best fit due to a star within the LMC as the lens is shown as the dotted curve. (See text for details.)

TABLE 1

Details of the microlensed stars and the derived masses of the lenses

Event	Magnitude (m_v)	Amplification (in blue)	Amplification (in red)	Event duration (d)	Impact parameter	Mass (M_\odot)
MACHO	19.6	~ 7.7	~ 7.7	33.9	0.17	0.1
EROS 1	19.3	$1 \pm 0.1 \text{mag}$	$1 \pm 0.1 \text{mag}$	44	0.425	0.002–0.32
EROS 2	19.3	$1.1 \pm 0.2 \text{mag}$	$1.3 \pm 0.2 \text{mag}$	53	~ 0.34	0.0002–0.44

The masses are derived under the assumption that the lensing is caused by stars within the LMC. Note that the lower limit to the mass of the lens comes from the requirement of a point source as explained in section 6. This is only a lower limit and consequently, the actual mass can be much higher than this limit. On the contrary, the upper limit comes from the fact that the tangential velocity of the lens cannot be much higher than the velocity dispersion (Eq 21). This is an exact expression and considering the usual distribution of the velocity dispersion, the mass is more likely to be closer to the upper limit. For the first event of Aubourg et al. we have used the radius appropriate for a subgiant and for the second event the radius appropriate for a normal star as indicated by their colours and luminosities. For a distance D between the source and the lens, the mass has to be multiplied by $100\text{pc}/D$. For the MACHO event, the amplifications and the impact parameter are from the extended source approximation.